PROJECT SUMMARY

Overview:

The proposed research aims to bridge the scale gap between local studies of carbon emissions in the Arctic, such as those from flux towers, and large regional scale emissions estimates from inversion modeling. The questions driving the proposed research are: What are the net late summer and autumn seasonal fluxes of carbon dioxide, methane, and nitrous oxide across the North Slope and Coastal Arctic Ocean? What are the primary surface land classes and associated mechanisms that contribute to these fluxes? What remotely-sensed products are the best proxy for the physical and biological processes that regulate the net flux and how do these vary regionally? How do the answers to the above questions vary depending on the scale of measurements used from local measurements up to regional scale inversion models? In order the answer these questions, aircraft eddy covariance measurements and vertical profiles are used to effectively scale process measurements from short eddy covariance towers to the regional scale, allowing for ascertaining how representative certain areas are of the larger North Slope with respect to flux of the major gases that contribute to changes in radiative forcing. Observations and modeling of fluxes and concentrations of isotopologues will help reveal the contributions of key source processes at local, landscape, and regional scale, a feature unique to this proposal. An analysis framework will be created to allow for the combination of in situ concentrations and fluxes with regional fluxes calculated using a transport model specifically adapted for Alaska. The proposed system is made up of custom built spectroscopic sensors, an air turbulence probe, a GPS systems, and the aircraft. The system would be deployed for two consecutive years, focusing on the late summer and early autumn time period.

Intellectual Merit:

The outcome of this proposal is centered on four main goals. The first two focus on bridging the scale gap between local scale and landscape scale flux measurements and then between landscape scale flux measurements in the boundary layer with regional scale estimates from inversion modeling. These first two directly lead to the ability to define the current late summer and autumn net flux of methane and carbon dioxide from the North Slope and adjoining Arctic waters which is required in order to establish a benchmark for quantitatively tracking the annual time series of net carbon flux from the Arctic. Finally, improvements to regional and global scale models require advancement in the current knowledge of methane and carbon dioxide flux sources in order to gain insight into how the net flux is expected to respond to a warming Arctic. As part of the proposal an empirical prior flux model for inverse modeling of methane fluxes will be created. The modeling, along with the in situ data, will allow fluxes to be calculated at the local, landscape, and regional scale to be used to answer questions outlined in the overview. Comparing the aircraft derived fluxes to local tower measurements and land classification maps in conjunction with information derived from the isofluxes will allow for the determination of which mechanisms are primarily responsible for the variation in emissions. Data, model runs, and analysis directly measuring the fluxes over regional scales close to the surface and measuring fluxes using inverse modeling will be compared to better understand the differences. Data will be used to evaluate which combination of environmental quantities and categorical quantities are best suited for predicting methane and carbon dioxide emissions to produce more accurate bottom up estimates from remotely sensed variables and will also be compared with existing carbon emissions models.

Broader Impacts:

Accurate, trusted forecasts of greenhouse gas emissions are critical for the improvement of global models that predict changes to temperature and to sea level. This proposal directly addresses the need to improve modeling capabilities when it comes to methane emissions and more generally the carbon budget for the Arctic. Specifically, data products from this proposal are used to evaluate and modify current regional emission models for the Arctic and contribute more broadly to the development of robust forecasts of carbon fluxes from this region. On a local level, data and modeling products from this proposal can be used to better inform local populations of the changes happening to their environment and help predict likely changes in the future. Understanding near-term changes to the Arctic environment is necessary for these communities to be able to plan for changes in food sources, land use, erosion, and town planning.

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For font size and page formatting specifications, see PAPPG section II.B.2.

*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

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Appendix Items:

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Appendix Items:

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I. Intellectual Merit

We propose to measure fluxes of carbon dioxide (CO_2) and methane (CH_4) and their isotopologues plus nitrous oxide (N_2O), ethane (C_2H_6), and water vapor (H_2O) from the North Slope of Alaska, building on the NSF project *Collaborative Research: Multi-Regional Scale Aircraft Observations of Methane and Carbon Dioxide Isotopic Fluxes in the Arctic.* We employ a small aircraft operating at altitudes from 10 m to 10 km, with air motion sensing for eddy covariance measurements (Figure 1). The proposed work provides (a) isotopically resolved fluxes correlated with underlying sources, (b) regional coverage for comprehensive analysis of carbon fluxes in this part of the Arctic basin, (c) direct coupling of the observations with other observing systems ranging from flux tower measurements to satellite remote sensing, and (d) coupling of the observations to a Lagrangian transport model to compare direct flux measurements to top-down estimates of regional emissions based on profiles in the atmosphere.

The key scientific questions to be addressed by this proposal, through the combination of observations and modeling, are: (i) *What are the net late summer and autumn seasonal fluxes of CO_2, CH_4, and N_2O across the North Slope and coastal Arctic Ocean?* (ii) *What are the primary surface land classes and associated mechanisms that contribute to these fluxes?* (iii) *What remotely-sensed products are the best proxy for the physical and biological processes that regulate the net flux of methane and carbon dioxide and how do these vary regionally?* (iv) *How do the answers to the above questions vary depending on the scale of measurements used from local measurements up to regional scale inversion models?*

The imperative for answering these questions stems from the fact that the northern latitudes are warming at twice the global mean [Serreze, 2011], making carbon stored in permafrost increasingly vulnerable to thaw and decomposition by microbes, potentially leading to large increases in CH_4 and CO_2 emissions. The thinning and loss of Arctic sea ice, an indication of the rapidly changing Arctic [Schweiger, 2011], as well as thawing permafrost, tap into the large carbon reservoirs containing both CH_4 within clathrates and organic carbon within the terrestrial permafrost system. Soils in the circumpolar permafrost region contain almost 1700 Gt of organic carbon, nearly twice the amount of carbon in the atmosphere [Schuur, 2015; Tarnocai, 2009]. Understanding the *potential* for release of this carbon requires understanding the biological and physical processes that control the emissions of CO_2 and CH_4 at the local, landscape and regional scales today, and how they respond to rapidly changing climate conditions.

Several campaigns have studied the net emissions of carbon from the Arctic either using bottom-up estimates from process based land models [e.g. Xu, 2016; Davidson, 2016; Belshe, 2013; McGuire, 2009] or top-down estimates from inversion modeling of tropospheric in situ and/or remote sensing measurements [e.g. Commane, 2017; Miller, 2016; Chang, 2014]. Many studies suggest that currently the Arctic is a net sink of carbon from CO_2 uptake, acknowledging that the balance between the uptake of CO_2 and the production of CH_4 and CO_2 will change over time. Recently, measurements have shown that early winter emissions of CO_2 are increasingly important, having increased by over 70% since 1975, and when these are taken into account, the North Slope region of Alaska is a net source of CO_2 to the atmosphere [Commane, 2017]. For methane, emissions estimates vary, especially when comparing process-based land-model estimates with top-down approaches [Xu, 2016; Chang, 2014]. Bottom-up estimates are limited by having to upscale plot-scale measurements in areas with highly heterogeneous landscapes on small spatial scales [Davidson, 2016]. As with CO_2, recent tower flux and aircraft measurements of CH_4 have shown that late season emissions account for as much as half of the annual mean CH_4 emissions from this region [Chang, 2014; Zona, 2016].

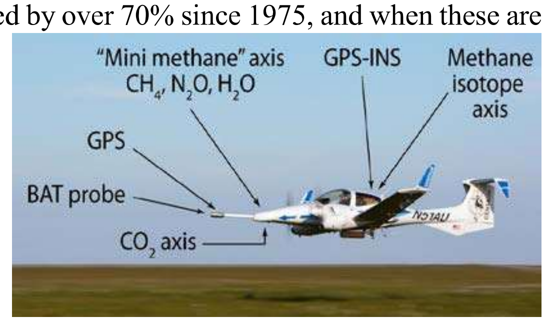

Figure 1. The FOCAL system as flown during flights in August, 2013 on the Alaskan North Slope. The measurement of carbon fluxes over broad regional scales with high spatial resolution requires a combination of instruments with high sensitivities and fast time response, the ability to measure vertical wind velocities with high time resolution and an aircraft capable of close tolerance flying with low flight-hour costs.

Nitrous oxide emissions in arctic and subarctic regions have long been assumed to be negligible due to severe nitrogen limitation [Martikainen, 1993; Potter, 1996]. However, recent studies using static-chamber methods have shown that, in some arctic ecotopes, N_2O emissions are quite high [Repo, 2009; Marushchak, 2011]. Other studies have shown the potential for high emissions after permafrost thawing [Elberling, 2010; Voigt, 2017], with the reported N_2O emissions approaching rates similar to some agricultural or tropical soils [Repo, 2009]. These studies challenge previous assumptions about cold-climate N_2O emissions, but they do not cover the spatial scale needed to determine if N_2O emissions in arctic and subarctic regions are significant. Understanding regional N_2O emissions will require the same analysis and bridging of scale gaps that we are planning for CO_2 and CH_4, and we therefore include it in this proposal.

We intend to use the aircraft eddy covariance measurements and vertical profiles to effectively scale process measurements from short eddy covariance towers to the regional scale (Figures 2 and 3), allowing us to look at how representative certain areas are of the larger North Slope with respect to flux of the major greenhouse gases (GHG). Observations and modeling of fluxes and concentrations of isotopologues and ethane will help reveal the contributions of key source processes at regional scale, a feature unique to this proposal. We will create an analysis framework to allow us to combine our in situ concentrations and fluxes with regional fluxes calculated using a transport model specifically adapted for Alaska. The system, Flux Observations of Carbon from an Airborne Laboratory (FOCAL), developed with prior NSF funding, is made up of the Harvard spectroscopic instruments, the Oak Ridge Associated Universities (ORAU) and NOAA Atmospheric Turbulence and Diffusion Division (NOAA/ATDD) developed Best Airborne Turbulence (BAT) probe, the GPS systems, and the Aurora Flight Sciences *Centaur* aircraft platform (Figure 1).

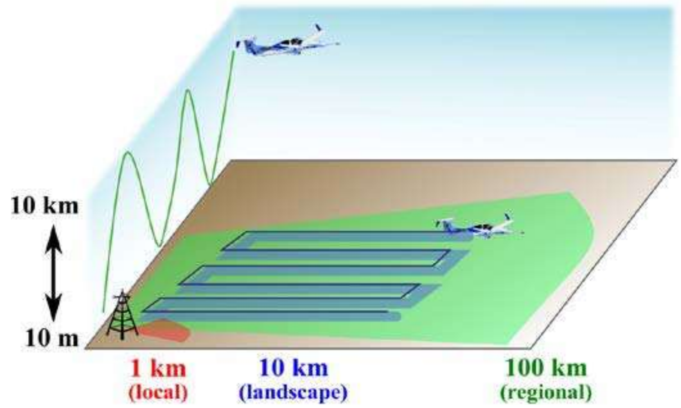

Figure 2. The proposed campaign will make measurements across multiple scales. Local scale measurements (1 km length scale; footprints ~1 km^2 (red shaded area)) are made by small flux towers. Landscape scale measurements (10s km length scale; footprints >10^2 km^2 (blue shaded area)) are made by FOCAL flying low in the boundary layer (blue line). Regional scale measurements (100s km length scale; >10^4 km^2 (green shaded area)) are calculated using concentration profiles made by FOCAL (green line) and inversion modeling.

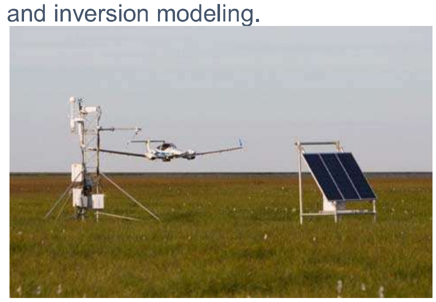

Figure 3. The close tolerance flight trajectories of the FOCAL observing system allow highly accurate comparisons with flux towers.

II. Proposal Objectives

Based on the results from the first FOCAL campaign, which demonstrated the ability to measure fluxes directly across the surface at different scales (see section IV), and the results of recent studies showing the importance of late season emissions from the North Slope, we define four goals for the current proposal:

1. **Bridge the scale gap between process-level or local studies and landscape scale flux measurements.**
2. **Bridge the scale gap between landscape scale flux measurements in the boundary layer with regional scale estimates from inversion modeling.**
3. **Define the current late summer and autumn net flux of CH_4 and CO_2 from the North Slope and adjoining Arctic waters to establish a benchmark for quantitatively tracking the annual time series of net carbon flux as the Arctic basin warms in the years and decades ahead.**
4. **Advance current knowledge of CH_4 and CO_2 flux sources in order to gain insight into how the net flux is expected to respond to a changing climate in the Arctic in the next decade and beyond.**

II.1. Bridging the scale gap between local scale and landscape scale flux measurements.

Numerous process level studies, conducted both in the field and in the laboratory, have been done or are taking place to better understand the mechanistic details controlling the production or uptake of methane and carbon dioxide within the soil or water column (e.g. Raz-Yaseef, 2017; Andresen, 2017; Lydia, 2016;

Li, 2016; Stackhouse, 2017; Olefeldt, 2013). These processes, including physical, chemical, and biological, must be incorporated into the analysis of Arctic ecosystems. Though the processes themselves occur at the microscale, through turbulent mixing in the lowest part of the atmospheric boundary layer (ABL, the lowest part of the atmosphere where turbulent and vertical mixing are strong) multiple processes occurring across the landscape may be combined leading to changes in atmospheric concentrations. As the landscape in the Arctic is heterogeneous on scales of 100s of meters, understanding how these small-scale processes vary over the landscape is required to integrate them into larger scales. Indeed, carbon emissions in the Arctic exhibit strong spatial and temporal variability [Xu, 2016]. Particularly challenging in the Arctic is the lack of roads in combination with the diversity of ecotopes. Aircraft measurements that can both be directly compared to local measurements (1 km^2 from towers) and can be extended to the landscape scale (10s to 100s of km^2) are particularly useful for bridging this scale gap and allow for understanding quantitatively how the local measurements can be interpreted within the larger landscape and regional context.

The ability to measure fluxes from an aircraft using eddy covariance with high spatial resolution (individual flux footprints as small as 3 km^2) applied over landscape scales provides a means of directly addressing several important scientific questions. By flying repeatedly along tracks near eddy covariance towers we can directly compare these measurements, with the towers providing continuous temporal coverage and the aircraft providing larger spatial coverage. Using the eddy covariance measurements from the aircraft in conjunction with land classification maps and other remotely sensed data products (e.g. surface temperature, radiation [see section V.3 for details]) allows us to detect the influences of soil moisture, land cover type, and air and ground temperature on high spatial resolution CH_4 and CO_2 fluxes as a function of geographic region.

II.2. Bridging the scale gap between boundary layer flux measurements and regional scale emission estimates.

Fluxes into the ABL are incorporated into the free troposphere via mesoscale processes (mountain circulations, sea breeze) and deep mixing in drier areas, giving rise to enhanced concentrations of emitted gases in the atmospheric residual layer (RL). Emissions estimates using measurements in the ABL and land vegetation models, often differ from those using measurements in the RL, which can represent areas as large as the State of Alaska [Commane, 2017]. There is a need to bridge the scale gap between the processes described above, which take place on the scale of square kilometers, and aggregated regional fluxes (10^4 km^2) that are deduced from inverse models constrained by *in situ* measurements from aircraft flying in the troposphere.

Our single aircraft, using the same instrumentation, can both directly measure the fluxes over local and landscape scales close to the surface and measure concentrations in the RL and free troposphere for inverse modeling. We will obtain profiles across the North Slope and in areas south of the Brooks Range to quantify the flux of carbon from the ABL into the free troposphere from these regions. By subtracting the dry mole fraction of methane in air entering the region from the column mean methane in the residual layer we can calculate the accumulated methane that represents the flux from the surface; the same steps will be used for carbon dioxide as well. Using the WRF-STILT model (see section VI) we can derive a surface influence function for each profile that can then be compared to both direct surface flux measurements from that area by FOCAL and to a surface emissions models. The contributions from fossil fuel flaring and biomass burning will be separated out using methane isotopologue ratios and the methane to ethane ratio (marking thermogenic methane), focusing the comparison on the biospheric contribution.

II.3. Evaluating the use of remotely-sensed land cover maps cross referenced to high resolution flux measurements to predict and to track methane emissions.

We have recently developed and tested methods to use remotely sensed quantities such as the enhanced vegetation index (EVI) and solar-induced chlorophyll fluorescence (SIF) and temperature to make accurate, spatially and temporally resolved predictions of carbon dioxide emissions or uptake [Luus, 2017; Commane, 2017]. This model, the Polar Vegetation Photosynthesis Respiration model (PVPRM), provides a prior flux model for inverse studies and for comparison with aircraft eddy fluxes.

Methane poses a harder challenge [Miller, 2016]. The diverse plant species and soils found throughout the Arctic vary in their contribution to methane oxidation, production, and transport and therefore it is reasonable to try to use land cover classes as a proxy for methane emissions [Li, 2016; Sayres, 2017]. Some work has been done to incorporate vegetative classes into process based models as these classes can represent physical properties not easily observed remotely. For example, the vascular system of sedge grass acts to facilitate passive transport of methane from the soil to the atmosphere and plant vegetation type can be used as a predictor or proxy of water table height, soil moisture, or other processes that have been shown to correlate with methane flux [Andresen, 2017; Davidson, 2016; Olefeldt, 2013].

The first FOCAL campaign (Section IV.1) showed how our measurements can be used to quantify carbon emissions based on land class defined from remote sensing instrumentation. This proposal would extend that work and would evaluate how a more comprehensive set of environmental quantities (surface temperature, EVI, SIF) and categorical quantities (land class, ground cover) can be used to predict methane emissions and produce more accurate bottom up estimates from remotely sensed variables. Many of these quantities will be directly measured by instruments on the aircraft (see section V.3). Others, such as land classification will be obtained from existing LandSat products [Macander, 2017].

Using the Flux Fragment Method, described in section III, the airborne fluxes measured by FOCAL can be divided by land class based on a footprint model and land classification map. Fluxes can then be fit to a model incorporating land class and other surface properties, temperature being likely the most important, to explain the variance in the surface fluxes. The model in turn can be used to predict surface flux and that prediction can be tested using data from different flights than the original data used to create the model. A similar approach has been applied successfully to subarctic wetlands in Finland [Li, 2016] and to three sites in Alaska [Davidson, 2016]. These studies were limited to discrete sites, versus our regional scales.

II.4. Advancing the mechanistic analysis of Arctic CH_4 flux sources, to gain insight into their response to climate change in the next decade and beyond – a key factor in the development of forecasts.

Predicting Arctic emissions of methane as well as understanding the drivers of carbon dioxide and methane sources and sinks is important for predicting future emissions from the Arctic and their effect on the global carbon cycle and radiative forcing. Besides fluxes of methane and carbon dioxide, fluxes of their major isotopologues ("isofluxes") can be used to help identify the processes most responsible for emissions or uptake. The addition of ethane to the measurement array provides another means of distinguishing fugitive methane release from gas wells from natural sources.

Repeated aircraft measurements of carbon fluxes will include the stable isotopologues of methane ($^{12}CH_4$, $^{13}CH_4$, CH_3D) and carbon dioxide ($^{12}CO_2$, $^{13}CO_2$, $^{12}CO^{18}O$). Isotopic measurements are reported in the δ notation referenced to a standard. For example, $\delta^{13}C$, is given by $\delta^{13}C = [(^{13}C/^{12}C)_{sample}/(^{13}C/^{12}C)_{standard} - 1] \times 10^3$, where the standard is Pee Dee Belemnite (PDB) [Criss, 1999] for carbon. The $\delta^{13}C$ of methane is different for thermogenic (natural gas, coal, etc.) sources versus biogenic sources (wetlands, ruminants, bacterial methanogenesis, etc.) (Figure 4). Very sensitive measurements are needed in order to separate different biogenic or thermogenic sources. The range of $\delta^{13}C$ between different source terms may be as small as 5‰, therefore high sensitivity isotope measurements are required in order to approach the desired 0.1‰ to 0.5‰ precision in $\delta^{13}C$. Our laser spectrometers have the capability to measure the isotopologues at ambient concentrations and at high sample rate (>10 Hz), not available in commercial systems.

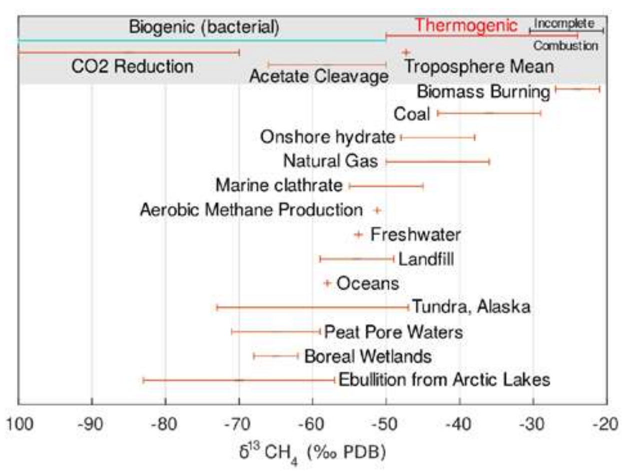

Figure 2. Measured $\delta^{13}C$ ranges for various general physical and biological processes (gray area) or sources (white area). Note that bars represent range of values found in the literature, often across multiple sites, not instrument uncertainty. Plus signs show mean values where range was not given. Data from Hershey et al. [2014], Vaughn et al. [2016].

Methane production via acetate cleavage or CO_2 reduction fractionate methane differently, producing methane with distinct isotopic ratios (Figure 4). Particular areas, or seasons, dominated by one pathway will show different mean $\delta^{13}C$ ratios.

Acetate cleavage occurs preferentially in wet, high organic matter soil and produces a higher net methane flux to the atmosphere than CO_2 reduction pathways [Vaughn, 2016; Hershey, 2014]. In contrast, CO_2 reduction is associated with low soil moisture and low organic matter and produces lower emissions, with CH_4 that is more reduced in the heavier isotope. As an example, a recent study in Sweden found a 10-15‰ shift in emitted methane associated with increasing methane emissions along a natural permafrost thaw gradient [McCalley, 2014]. This shift in methane was found to be caused by a shift in the production pathway from CO_2 reduction to acetate cleavage.

Combining the Flux Fragment Method with a land class map, as described in sections II.3 and IV, will allow us to differentiate which land classes have the highest emissions and how these vary over the time period that we are measuring. Combining physical information inferred from the land class, such as the wetness of the soil, with the isotopologue measurements can further be used to help distinguish the mechanisms responsible for controlling the net emissions from each land class.

III. Measuring Air-Surface Exchange from Aircraft

Eddy covariance is a direct way to determine the exchange of mass, momentum, and energy between the atmosphere and the surface. To determine mass exchange, trace gases are sampled at 10 Hz by the FOCAL instrument. The covariance of the dry-air mixing ratio of these gases [Webb, 1980] with the turbulent vertical wind component determines the flux. Sampling is restricted to be within 30 m of the ground, in order to justify the assumption that the measured flux is equal to the exchange at the surface [Mahrt, 1998]. Flux measurements from fixed surface sites, important complements to the airborne measurements, provide extended temporal coverage at selected locations.

Airborne turbulence measurements apply Newtonian (low-speed) general relativity to measurements made in the airplane's reference frame to yield turbulent wind in the earth's reference frame [Leise, 2013]. High sample rate (50 Hz) and precise synchrony are required for both the sensor's motion and the sensor-relative wind. Four samples define the minimum effectively resolvable eddy size, about 5 m at the Centaur's speed (60 m/s). Since turbulent fluctuations can be less than 0.1 m/s, the aircraft inertial velocity and wind speed must be known to better than 0.1 m/s. The Centaur uses a small Inertial Navigation System integrated with a GPS (GPS/INS) to report its linear velocity over the surface as well as its roll, pitch, and heading, all at 50 Hz. The low-frequency component (less than 1 Hz) of the Centaur's velocity is extrapolated to the probe's location to mix with the high-frequency component measured directly at the probe. The relative airflow is determined from the distribution of induced pressure over the BAT probe's hemispherical surface. One absolute pressure and three pressure differences are taken over nine ports. From these four pressures plus a temperature come the five relative-flow parameters: static pressure, static temperature, and three components of the airflow relative to the probe [Dobosy, 2017 and references therein].

Analysis of the 2013 FOCAL Alaska campaign demonstrated the capability to determine landscape scale variations of CO_2, CH_4, N_2O, and H_2O fluxes from the aircraft data and to attribute them to land cover classes, using two complementary approaches. The running flux method (RFM) [LeMone, 2003; Mann and Lenschow, 1994] is commonly used to analyze airborne fluxes. We compute Reynolds averages over an appropriate length, using overlap to provide smoothed interpolation. The RFM quantitatively describes the relation between measured flux and underlying surface features of a scale comparable to the averaging length or larger. In the Arctic in 2013, the shallow ABL depth gave rise to small turbulence scales. Ogive analysis showed a 3 km averaging length to suffice for flux computations.

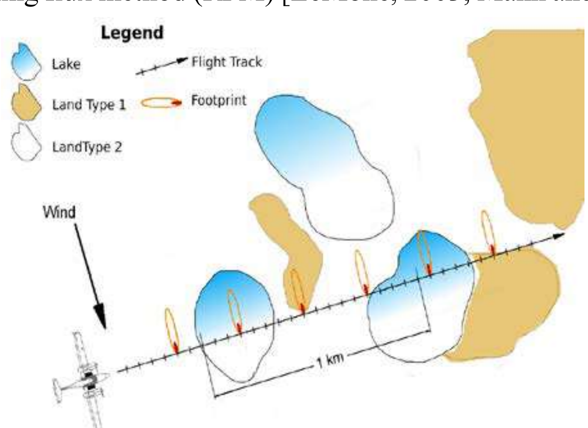

Figure 3. Illustration of the flux fragment method (FFM) allowing for fluxes to be grouped by land classification.

The flux fragment method (FFM) [Kirby, 2008; Dobosy, 2017; Sayres, 2017] uses a conditional sampling scheme compiling a flux from many 1s "fragments" of flux of a quantity, such as CH_4 along a transect (Figure 5). The fragments do not constitute a

Reynolds average individually, but provide a meaningful flux estimate only in aggregate. Fragments are grouped by surface class, determined from footprint estimation. The FFM is applicable in a region that is heterogeneous on small scales (100 m to 10 km), but relatively homogeneous on large scales. The spatial average over each group provides the mean flux from the associated surface class. Initial assessments of the data indicated that the FFM is well suited for application to the North Slope, where arctic tundra is interspersed with thermokarst lakes, bogs, fens and bare ground. The FFM is executed in six steps: (1) Classify the region using a current classified land-cover image at 100 m resolution or better. (2) Measure flux repeatedly over an established transect at typically 10 m to 30 m above ground, as low as safely possible. (3) Assign a base state, in principle the deterministic (nonturbulent) mesoscale component of the flow using the whole flight leg. (4) Calculate flux fragments, 1s sums of squares and cross products of departures from the base state. (5) Apply a footprint model to estimate the level of influence of each surface type on each fragment. (6) Group the fragments by land class and sum the fragment groups, dividing by their accumulated length, to calculate mean fluxes. The number of fragments necessary to provide a robust result is determined by bootstrap resampling and Ogive analysis. Our data quality checks include assessment of spectra and cospectra of component data streams. In the proposed work we will develop automated QA/QC to accept or reject data from each flight segment as for the 2013 campaign this was done manually adding considerable time to the analysis.

IV. Results from Prior NSF Support

IV.1. (a) NSF Award #: 1203583, $2,818,001, 9/1/2012-8/30/2014

(b) Collaborative Research: Multi-Regional Scale Aircraft Observations of Methane and Carbon Dioxide Isotopic Fluxes in the Arctic. PI – Anderson, Co-PIs – Meyers, Langford, Co-I – Dobosy.

(c) Summary of Results – Intellectual Merit – The NSF polar programs office funded the first test flights of the FOCAL system. The pilot project consisted of test flights of the instrument array with the Centaur aircraft in Manassas, VA and then a preliminary science flight series to Alaska's North Slope in 2013. To measure methane emissions over large areas of the North Slope, the FOCAL system was flown out of Deadhorse Airport, Prudhoe Bay, AK. We summarize the results here, with more details contained in the publications listed in section IV.1.(d). Data presented in this section were obtained during six flights between August 13 and August 28 (yellow flight tracks in Figure 6). During three of these flights the aircraft made repeated passes near the NOAA/ATDD flux tower that was set up for comparisons as part of the project. The other three flights were flown as grid patterns over large regional areas (~50x50 km^2) to better sample the heterogeneity of different land classes over a large region. These flights consisted of both profiles from the bottom of the boundary layer (~5-10 m) up to ~1500 m altitude and long transects (~50 km) at low altitudes (<25 m) that are used to access surface flux using eddy covariance. The two data analysis methods discussed in section III, the RFM and the FFM, were employed to generate the results treated here.

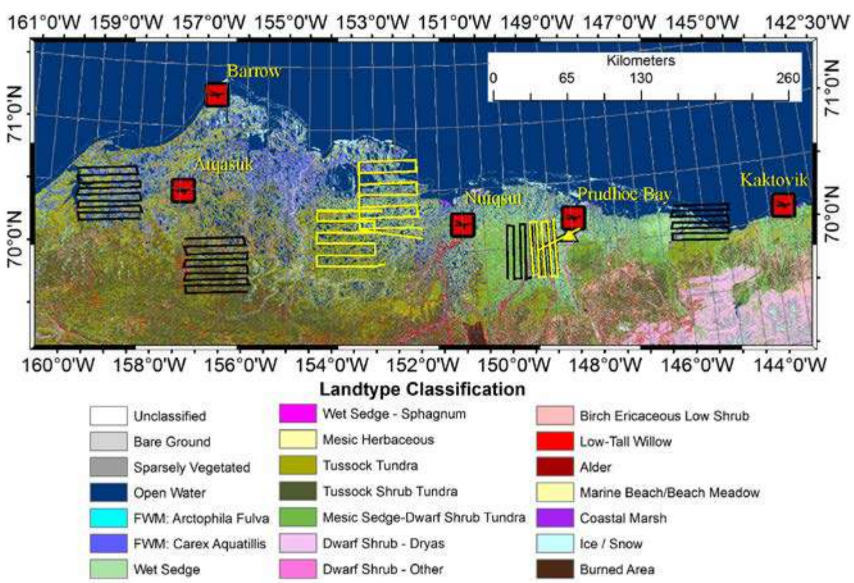

Figure 4. Land cover map with major towns and airports indicated. Low level (<25 m) flight tracks flown during the 2013 campaign (yellow) and notional additional flight tracks for the proposed campaign (black) are shown. Location of flux tower from 2013 campaign shown as yellow triangle.

Low altitude flying and logistics: The work proposed requires flying at low altitudes over the tundra. During the mission to Alaska in 2013 the Centaur was repeatedly able to transit to the region of interest and make multiple passes over the target flight legs. To evaluate the dependence of the measured methane flux on the height above the ground, a regression of 3-km running fluxes against the height above ground for one of the flights was run to assess the correlation of flux with altitudes ranging from 5 to 45 m. For all subsequent flights, the flux altitude was defined as being below 25 m above ground level. CH_4 profiles from the flights (Figure 7) show increased variation in mixing ratios below 100 m, with the concentration falling to background levels above 500 m.

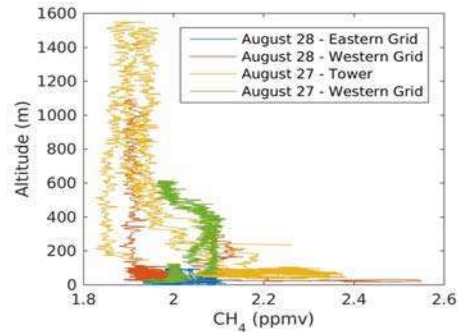

Figure 5. Profiles of methane mixing ratio for four different flights on the Alaska North Slope showing the large variability in the lowest layer of the ABL.

Comparison with eddy covariance tower: On August 13, 25, and 27 FOCAL flew passes over a constant northeast/southwest track, 50 km long, near the NOAA ATDD tower affording direct comparison between eddy-covariance flux measured from the tower and from the aircraft using both the RFM and FFM (Figure 8). A succinct summary of the cross comparison between the airborne flux measurements and the flux tower measurements is presented here (see Sayres, 2017 for a more detailed discussion). Both the summer daytime and autumn evening flights showed that when there is reasonable overlap between the tower and aircraft footprints, the flux measurements from the aircraft agree with those from the tower, adding another level of validation to the aircraft data. The flight on August 13 (DOY-225) was on a day when turbulence was strong and soil temperatures at 10-cm depth were 10-14 °C. There was excellent agreement between the flux tower measurement for methane and the FOCAL airborne system. The warm soil produced strong methane emissions, and the flux measured at the tower matches the local RFM flux near the tower as well as the FFM flux from the distributed patches of wet sedge.

On August 25 (DOY-237) the local RFM produced a good match with the tower, but not the (distributed) FFM. Plotting the entire set of RFM fluxes from the 25th (Figure 9), showed that the tower was in a local hot spot, explaining this anomaly. Plots of methane flux against the height of airborne measurement or strength of turbulence (σ_w) suggested little dependence on these variables. This flight highlights the hazards inherent in relying on point measurements, which may be in non-representative locations, to estimate regional fluxes. Also note in the middle lower panel of Figure 8 that the flux of 1 $\mu g \cdot m^{-2} \cdot s^{-1}$ at the tower, though isolated in space, was not isolated in time. Finally, for August 27 (DOY-239), the aircraft measured significantly lower methane flux by local RFM than the tower. The results from the three near-tower flights represent three different situations. On the flights of August 13 and 25 the footprint analyses indicate the highest probability of influence on the RFM flux (3-km length centered nearest the tower) is sedge. On August 27 lakes make up more than half of the RFM

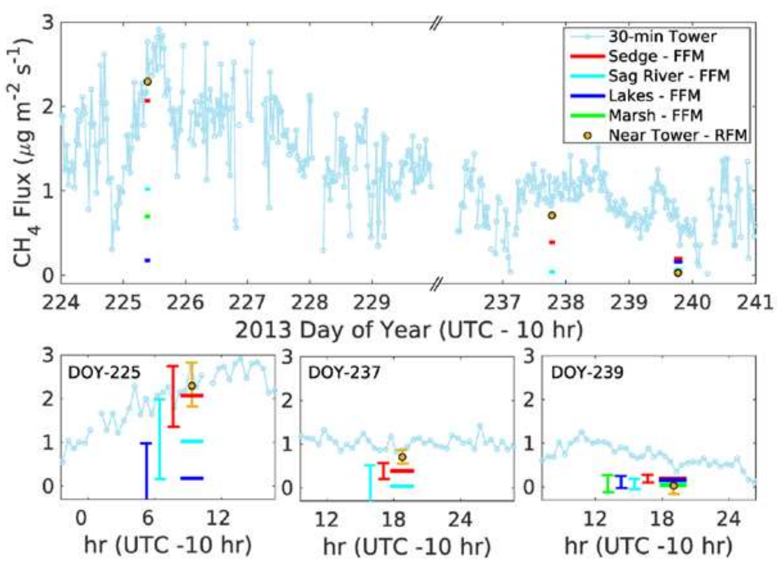

Figure 6. Methane flux measured from the tower compared with the FOCAL system. Tower fluxes (top plot) are 30-minute means plotted versus day of year (DOY). Each flight consisted of repeated passes near the tower. The orange circle gives the mean over these passes of the RFM-determined 3 km flux centered nearest the tower. Fluxes by FFM were aggregated by surface class over the whole flight. The length of the line along the time axis represents the period over which the data were taken. Lower panels show details for each flight day, labeled by DOY, with vertical bars showing the 95% confidence interval based on bootstrap analysis. Bars are offset along the x-axis for clarity. (From Sayres, 2017)

flux footprint. Lakes have been shown to be sporadic hot spots of methane ebullition, but at least at the time of flight these lakes showed very low methane emission.

Regional coverage: During August 2013, FOCAL measured methane flux from a variety of ecotopes across the North Slope (Figure 10). The tower data show that carbon dioxide and latent heat exhibit strong and regular diurnal cycles, but methane generally exhibits a weak diurnal cycle [Fan, 1992]. This discussion, therefore, will focus on the seasonal change and the methane-emission characteristics of the various surface classes. In order to distinguish the contribution to the total methane flux from individual land classes and to assess the variability across ecotopes, the data are filtered to only include flux fragments where at least 85% of the crosswind-integrated probability density comes from a single land class. Varying the threshold between 80% and 95% produces only a small effect on the quantification of flux from each land class. We find that 85% is a good compromise between singling out individual land classes while still retaining a sufficient dataset.

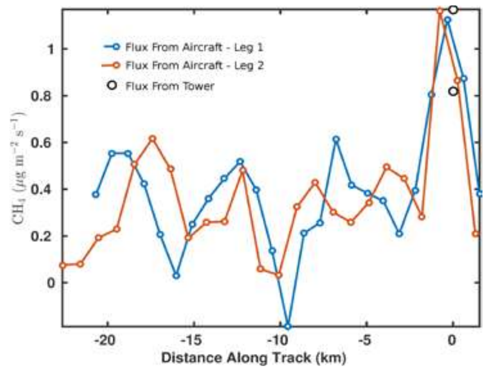

Figure 7. Plot of methane flux derived using RFM versus distance from flux tower for two flight legs on August 25. Positive (negative) distance is East (West) of the tower position. The East to West transect (blue) was flown 30 minutes after the West to East transect (orange). Black circles are the methane flux measured by the tower at the nearest time to when the aircraft passed the tower.

Airborne measurements made during August 2013 are consistent with findings from other studies. Olefeldt [2013] reported sites dominated by sedge and wet soils having methane emissions ranging from 0.46 to 1.6 $\mu g \cdot m^{-2} \cdot s^{-1}$ across multiple permafrost sites. Other studies at single locations fall into this same range. Harazono [2006] measured methane fluxes from a wet sedge site in Happy Valley, AK, during August of 1995 ranging from 0.38 to 1.5 $\mu g \cdot m^{-2} \cdot s^{-1}$ and Sturtevant [2013] measured wet sedge near Barrow with emissions of 0.39 ± 0.03 $\mu g \cdot m^{-2} \cdot s^{-1}$ with short periods of higher emissions up to 1.1 $\mu g \cdot m^{-2} \cdot s^{-1}$. Emissions from mesic-sedge sites near the Sag River, though south of the areas measured by FOCAL, showed fluxes of 0.35 to 0.58 $\mu g \cdot m^{-2} \cdot s^{-1}$ in the first half of August falling to 0.12 to 0.23 $\mu g \cdot m^{-2} \cdot s^{-1}$ in the second half of August [Harazono, 2006].

Emissions from lakes tend to be more variable than the land classes. Reported annual mean emissions from individual lakes in the North Slope [Walter, 2007; Sepulveda-Jauregui, 2015] ranged from 0.25 to 6.3 $\mu g \cdot m^{-2} \cdot s^{-1}$. FOCAL sampled emissions from several individual lakes, including five on August 13. The fluxes for individual lakes ranged from 0 to 2.6 $\mu g \cdot m^{-2} \cdot s^{-1}$ with a mean for all lakes sampled of 0.18 $\mu g \cdot m^{-2} \cdot s^{-1}$. On August 27 four lakes were measured with emissions ranging from 0.09 to 0.18 $\mu g \cdot m^{-2} \cdot s^{-1}$. The mean methane flux from all lakes over the period of the flights showed small or negligible fluxes, except for lakes sampled on the morning flight of August 28 (aggregate mean of 0.36 $\mu g \cdot m^{-2} \cdot s^{-1}$). That was the only sampling day with fluxes from lakes that were statistically significantly.

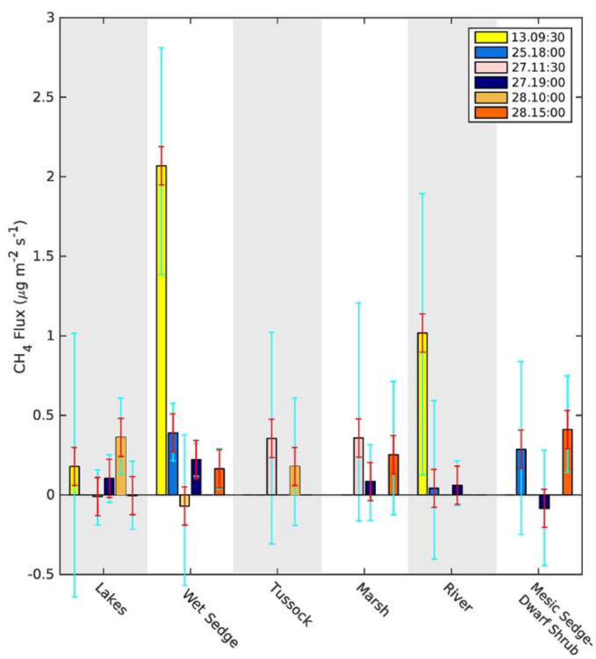

Figure 8. Mean methane fluxes by land surface class derived using the FFM for each of six flights as given in the legend. Dates of flights are given as day of month in August followed by the time of the middle of the flight. Bars give the instrument uncertainty (red) and the 95% confidence interval as calculated using bootstrapping (blue). (From Sayres, 2017)

Regional Nitrous Oxide Emissions: While initially not intended to be a primary product of the campaign, N_2O absorption lines are present near the CH_4 and H_2O lines recorded using the methane instrument that is part of FOCAL. With recent interest in Arctic N_2O emissions [Elberling, 2010; Voigt, 2017; Repo, 2009;

Marushchak, 2011], we analyzed our N_2O data and calculated regional estimates on a flight by flight basis. With FOCAL, we were able to measure N_2O fluxes from these landscapes over regions spanning hundreds of kilometers. Our results show that some regions show very low N_2O emissions, but several areas have N_2O emissions consistent with high values reported by recent studies [Wilkerson, 2018]. Our data support nascent concerns for the role of Arctic N_2O emissions globally.

Summary of Results – Broader Impacts – Methods developed as part of the 2013 analysis are also applicable to measuring fugitive carbon emissions from oil and gas wells and for developing regional carbon emissions budgets in the contiguous United States.

(d) Wilkerson, 2018 (submitted); Sayres, 2017; Dobosy, 2017; Healy, 2016; Munster, 2016; Dumas, 2014; Dobosy, 2013.

(e) Data, including gas concentrations, fluxes, footprints, and ancillary data for flights and tower have been archived at the Harvard Dataverse under doi:10.7910/DVN/YM70Y7 [Sayres, 2018] and the NSF Arctic Data Center [Sayres, 2014].

(f) Relation of previous work to current work – The previous funded proposal was for a limited test deployment of the FOCAL system to prove the ability to fly at close tolerance in the Arctic and measure fluxes of carbon. That test flight series provided the ground work for a full science mission deployment and is the basis for the proposal described here.

IV.2. (a) NSF Award #: 1337512, $315,000 ($450,000 with cost sharing), 08/01/2015 to 07/31/2016

(b) MRI: Acquisition of Mesoscale Network of Surface Sensors and Solar Spectrometers. PI- Wofsy

(c) Summary of Results – Intellectual Merit – The goal of this MRI was to use novel measurement approaches to understand and predict the spatial and temporal distributions of chemical species emitted in urban regions, in order to determine emission rates and provide a tool to assess the efficacy of emission reduction programs. It is challenging to use data exclusively from surface sensors, because emitted species have high variance near the ground due to the influence of nearby sources and small scale winds. This project designed and implemented a new type of atmospheric observing network for cities exploiting the analytical power of total column observations. Using funds from the grant, we installed a conventional surface network of observations for CO_2 and CH_4 in the Boston area plus spectrometers that measure the column amounts of pollutants by observing the spectrum of the sun. We positioned matched spectrometers upwind, inside, and downwind of the city. The vertical dimension provided by our novel network was intended to overcome the limitations of surface networks, and provide new low-noise, high fidelity metrics. The signals have the low variance and clarity that we sought. We also developed powerful new methods for analyzing data from urban networks, to derive emission rates from part or the whole city.

Summary of Results – Broader Impacts – Urban environments lie at the core of many environmental issues: most of the greenhouse gases and pollutants emitted globally originate in cities, and urban dwellers are exposed to elevated levels of toxic substances and health risks. Analysis from this project of emissions of natural gas in the Boston urban region, a subject of concern for the environment and to utility regulators, observed loss rates of 2-3% of the gas entering the region which is comparable to, or larger than, the full extent of losses upstream in the natural gas production and transmission sectors.

(d) Chen, 2016a; Hedelius, 2016; McKain, 2015; Viatte, 2017.

(e) Data archived at Harvard's Dataverse network under doi:10.7910/DVN/J2YPX3 [Chen, 2016b].

IV.3. PI - Roisin Commane, Columbia University. N/A

V. Instrumentation and Experimental Approach

The FOCAL observing system is made possible by the convergence of three unique systems: the carbon isotopologue instrument array developed at Harvard University with NSF MRI and polar programs funding, the BAT probe developed by ORAU personnel in conjunction with NOAA/ATDD, and the Centaur aircraft developed and operated by Aurora Flight Sciences. We present here the main instrument subsystems and highlight improvements since the first field deployment.

V.1. Measurement of gas mixing ratios and isotopologue ratios

To characterize carbon exchange and to distinguish biological production from methane leaks or biomass burning the carbon instrument must measure species with sufficient precision and at sufficient temporal resolution for use with the eddy covariance technique. The carbon isotopologue instrument uses three detection axes in order to sample the molecules of interest. All three axes draw air from inlets located 8 cm aft of the BAT probe turbulence measurements. Flow of air through all the axes is controlled by two dry scroll pumps. Air from the inlets pass through 1.25 cm tubes into the forward nose and luggage bay sections of the aircraft. The pressure of the air is controlled by proportional solenoid valves and a pressure control board that uses pressure measured within each of the measurement cells to feedback on the valve orifice position. The forward luggage bays contain two detection axes. Axis 1 (Methane) uses the Reinjection Mirror (RIM) - Integrated Cavity Output Spectroscopy (ICOS) technique to measure $^{12}CH_4$, $^{13}CH_4$, CH_3D, C_2H_6, and H_2O. Axis 2 (Carbon Dioxide) uses differential absorption to measure $^{12}CO_2$, $^{13}CO_2$, and $^{12}CO^{18}O$. Axis 3 (Nitrous Oxide/Methane), located in the backseat area uses ICOS to measure N_2O and $^{12}CH_4$. Scroll pumps, calibration gases, and the main computer and data system are located in the backseat area of the aircraft.

V.1.1 Methane isotopologue axis

The CH_4 axis uses the ICOS technique in order to measure the very weak $^{13}CH_4$ and CH_3D lines as well as $^{12}CH_4$ [Witinski, 2010]. ICOS uses a high finesse optical cavity composed of two high-reflectivity mirrors ($R > 0.9997$) to trap laser light for a period of 1–10 μs producing effective path lengths 10^3 times the mirror separation. This provides extremely high signal to noise observations in flight (Figure 11.B). The Anderson group at Harvard has used ICOS for several flight instruments since 2001 [Paul, 2001; Sayres, 2009; Witinski, 2010; Sayres, 2017]. For the proposed mission we will use a methane axis, modified from the one that flew in 2013, that uses a recently developed approach called reinjection mirror (RIM) ICOS [Leen, 2014]. A spherical mirror with a hole in it is used to re-inject the light normally lost from the high reflectivity mirrors. In our lab we have successfully increased the effective power from the laser by a factor of 16, which directly increases the precision of the instrument. Using this technique we can detect the methane isotopologues with a smaller cell than was used in the first campaign, thus allowing for the isoflux to be measured at the same time as the methane flux without the need for a second larger cell. This frees up considerable volume and weight in the back seat area of the aircraft. The new system will be a three laser system to measure CH_4, $^{13}CH_4$ and H_2O, CH_4 and CH_3D, and CH_4 and C_2H_6, respectively, where the laser beams are co-aligned before entering the RIM-ICOS cell. By asynchronous operation of the lasers we can record spectra from all three and coadd to 10 Hz for eddy covariance flux measurements. The lasers are all in the 3.4 μm region and use the same set of high-reflectivity mirrors and detector. The high sampling rate of vertical wind measurements demands correspondingly fast concentration measurements made possible due to the ICOS cell having a small sample volume and high flush rate (17 Hz).

Due to the high concentrations and variability of water in the troposphere, water vapor measurements are required with any trace gas measurements in order to quantify dilution effects and spectroscopic broadening effects. Well defined absorption features of water vapor can be obtained in the same sweep of the laser, therefore the same sample cell will provide measurements of water vapor along with methane. Periodic calibrations in flight, referenced to calibrated gas cylinders, are used to track instrument drift over the course of the flight and from flight to flight. Two gas cylinders are mounted in the rear of the aircraft. Each is filled from a standard tank that contains air with known amounts of CH_4, CO_2 and N_2O and their isotoplogues. The two tanks span the range of

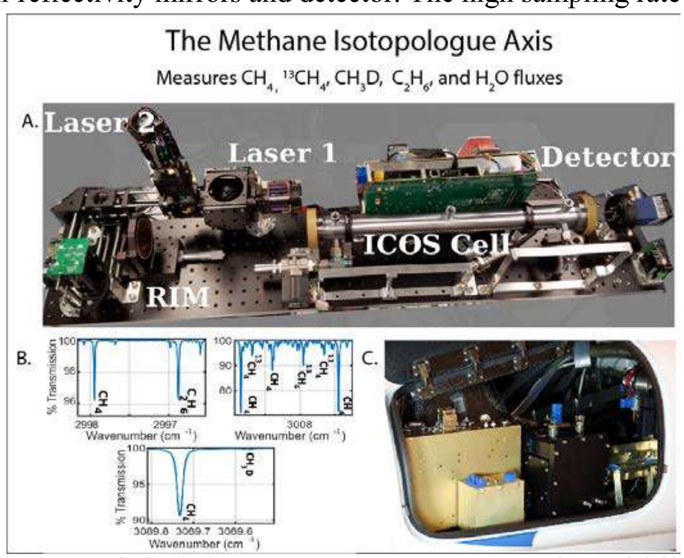

Figure 9. (A.) The new methane isotopologue axis (RIM-ICOS) shown as a two laser system. The instrument that will fly will have a third laser for measuring ethane. (B.) The three spectral regions used to measure the methane isotopologues. (C.) A picture of the methane axis that flew in 2013 in the luggage bay of the Centaur. The newer version will look similar once packaged, except for a longer cell length to account for the RIM.

expected mixing ratios and these tanks are themselves calibrated against NOAA and WMO standards in our laboratory. Calibration cycles typically are done once every 30 minutes in flight by opening a valve near the inlet pressure control valve, that is connected via quarter inch tubing to the air calibration deck.

V.1.2 Nitrous Oxide axis

The first campaign showed large variability in N_2O fluxes so we will measure N_2O fluxes again, using the methane axis that flew in the first campaign. For the proposed deployment it will be relocated to the back seat area and provide measurements of N_2O as well as redundant measurements of CH_4 and H_2O at a different wavelength than the methane axis described above. This axis is an ICOS cell (25 cm in length; 5 cm diameter mirrors) displayed in Figures 11.C and 12.

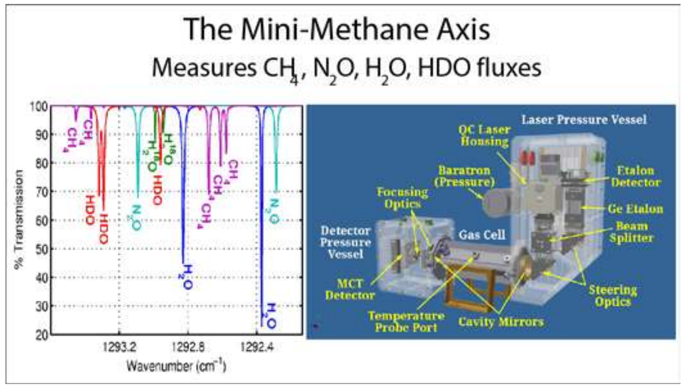

Figure 10. (left) Spectral region used to measure $^{12}CH_4$, N_2O, and H_2O (right) CAD drawing detailing the main elements of the axis. A picture of the axis as it flew in 2013 is shown in Figure 9.

V.1.3 Carbon Dioxide isotopologue axis

The CO_2 axis uses a 4.3µm laser to measure CO_2, $^{13}CO_2$, and $CO^{18}O$ mixing ratios. The cell path length only needs to be 10 cm in length. The CO_2 axis employed here uses the differential technique described in Santoni, [2014]. The instrument that flew in 2013 used a single multi-pass direct absorption Herriott cell. We will combine the differential absorption cell design with the updated lasers, detectors, and electronics that have previously flown. Gas from a standard tank flows through a reference cell and both cells are maintained at the same pressure and temperature. Differencing the spectra from the two cells allows for small changes in temperature, pressure, or laser characteristics to be accounted for, thus improving our short term and long term precision. Remaining drifts are accounted for by periodically switching to calibrated gas standards. The cell is designed to have a flush rate of 30Hz to work in conjunction with the BAT probe and provide a flux measurement using the eddy covariance method.

V.2 BAT probe

ORAU in conjunction with NOAA/ATDD developed the Best Airborne Turbulence (BAT) probe as a pioneering low-cost solution for mobile atmospheric turbulence measurements (Figure 13) [Crawford, 1990; 1992]. The FOCAL instrument draws on their extensive experience in airborne turbulence measurements from the Arctic tundra to subtropical ocean systems. A GPS/INS system located near the CG of the aircraft and two GPS antennas, one located on the BAT probe and the other located on top of the main cabin, provide for the movement of the BAT probe and Centaur relative to the Earth's surface. Fluxes of trace gases are covariances between turbulent winds and fluctuations of gas concentration. The BAT probe was designed to accurately measure turbulent winds from a moving aircraft and, using accelerometers and GPS/INS, to relate those winds to the surface. It is very important for the accuracy and uncertainty analysis of the flux product that the wind probe be directly tied to the same electronics that control the concentration measurements. In FOCAL, the BAT probe's data are processed by the same DACS and recorded by the same computer as the other instruments. The BAT probe

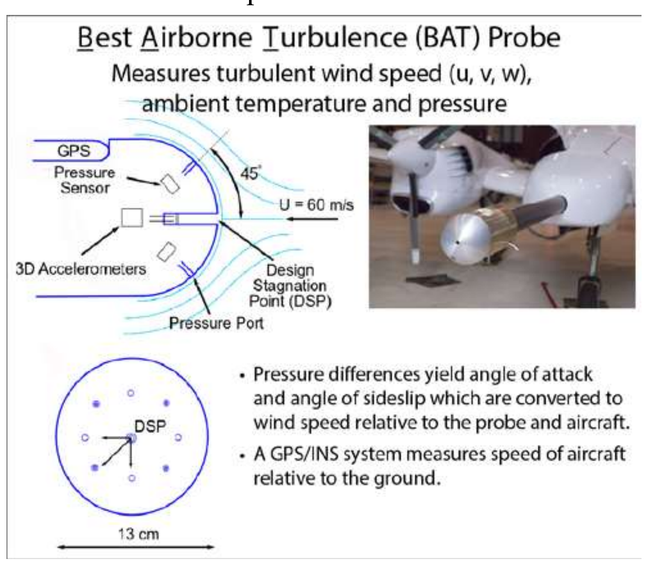

Figure 11. Shown in the left panel is a schematic of the probe's sampling geometry. Shown in the upper right is the BAT probe mounted on the Centaur aircraft.

digitizes 1600 S/s for low-pass filtering and subsampling at 50 S/s to suppress aliasing. The wind measurements are synchronized with the 50 Hz signal from the GPS/INS system.

V.3 Auxiliary measurements

There are several other small instruments that augment FOCAL's capabilities. In the 2013 campaign, we flew a radar altimeter for height above ground, which is essential for accurate footprint calculations, and a visible camera, which provides a visual record of the terrain directly under the aircraft to check the accuracy of remotely sensed products that provide primary landscape classification. For the proposed campaign, we will integrate several additional small, commercially available instruments. A FLIR camera for measuring inundation of the surface and surface temperature and a nephelometer to help identify air masses affected by biomass burning or other pollutants. In addition, we will fly two multi-spectral or hyperspectral radiometers: one looking up and one looking down. These will provide the following four components: down-welling visible light from the sun, down-welling infrared from the sun and the atmosphere, up-welling visible (reflected), and up-welling infrared emitted from the surface.

V.4 Centaur aircraft

The Centaur is a twin-engine aircraft, certificated under the FAA for operations worldwide, and has several characteristics that make it an ideal platform for the work proposed here. The aircraft is economical, with its electronically controlled turbo-diesels together consuming just 9 gallons of Jet–A fuel per hour, which is roughly half the rate of many light twins. Because of the twin engine configuration, the entire center fuselage is available for instrumentation and sampling. The Centaur is electrically and structurally well-adapted for carrying a sophisticated scientific payload, having ample power (1500 W) from two alternators and ideally located hold points for the probe and the spectroscopic equipment. Finally, the operating cost of the Centaur is $5300 per day and $600 per flight hour.

VI. Plan for Regional Scale Fluxes from FOCAL Observations

The proposed work will tie together high resolution, landscape-scale and regional scale flux measurements using an atmospheric transport model.

VI.1 Inverse modeling at regional scales: Atmospheric Transport Model

pWRF-STILT is a polar variant of the Weather Research and Forecasting Model (WRF), coupled to the Stochastic Time-Inverted Lagrangian Transport model (STILT). WRF is run with 3.3 km grid spacing in the innermost domain over Alaska, with surface features primarily related to the Noah land surface model [Chen and Dudhia, 2001], optimized for polar applications [Wilson, 2011]. Previous studies have used boundary and initial conditions derived from the NASA Modern Era Retrospective-analysis for Research and Applications (MERRA, Rienecker, 2011). Work since Commane [2017] has updated the boundary and initial conditions to run with MERRA2 and ERA5 (released by the European Center for Medium-Range Weather Forecasts, ECMWF). WRF exhibited a ~1K cold bias in spring air temperatures close to the Arctic ocean coast in v3.4.1 [Henderson, 2015], but the MERRA2 and ERA5 initial testing suggests this bias has been reduced and will be evaluated extensively. This model-data adjoint framework (WRF-STILT) has been developed over the last 10 years at Harvard and AER, Inc. [Lin, 2003; Hegarty, 2013], and elsewhere, and now provides a robust tool to obtain urban, regional and continental scale fluxes from atmospheric concentration data [McKain, 2012; Miller, 2013]. pWRF-STILT follows the trajectory of 500 air parcels (particles) released from the receptor position backwards in time over the previous 10 days, where the motion of each parcel includes advection by the large-scale wind fields and random turbulent motion, independent of the other parcels. The proportion of particles residing in the lower half of the planetary boundary layer determined the influence of surface fluxes on the measured mole fractions. The two dimensional "footprint" is calculated for each particle at 3 hour intervals on a 0.5^o x 0.5^o grid over the 10-day travel period of the particles, defined as the response of each receptor measurement to a unit emission at each grid square (units in mixing ratio per flux: CO_2 μmol mol^{-1}/ μmol m^{-2} s^{-1}; CH_4 nmol mol^{-1} / nmol m^{-2} s^{-1}). When the footprint is multiplied by an *a priori* flux field we get the contribution to the mixing ratio measured at the receptor, from each point on the surface. The best-fit flux field is obtained by optimizing the surface fluxes using a powerful combination of Bayesian and geostatistical methods, as outlined by Miller [2013; 2016]. Lagrangian methods such as used in STILT minimize numerical diffusion, and through coupling to a mesoscale weather model, meteorological realism and mass conservation are achieved. These aspects enable the Lagrangian approach to compute realistic surface fluxes and their uncertainties for measurements from a variety of platforms including towers, aircraft, and satellites.

VI.2 FOCAL domain and model setup

Placement of nested modeling domains will be employed as required, following the template developed for CARVE. Most of Alaska will be covered by a 10 or 3.3 km polar stereographic, and higher resolution grids will be introduced in the key experiment areas as needed to resolve mesoscale motions. The substantial orography of Alaska is represented by the underlying high-resolution topographic input field. Figure 14 shows one set of simulations of CARVE CO_2 data for the North Slope domain, illustrating the powerful linkage of landscape and regional scale fluxes enabled by the in situ data and models. The figure demonstrates the excellent fidelity between observations and model obtained using WRF-STILT with a spatially/temporally resolved source field (see below). In the case of CARVE data for CO_2, the analysis of a full summer of data led the CARVE team to infer tight constraints on the overall net carbon balance and the daily cycle of respiration and photosynthetic uptake. The FOCAL platform will allow us to make this type of large-scale determination *and* to define how the high spatial resolution, landscape-scale elements on the North Slope contribute. **This linking of scales is the core of the proposed work, providing the key to disentangling the many influences on fluxes of CO_2 and CH_4.**

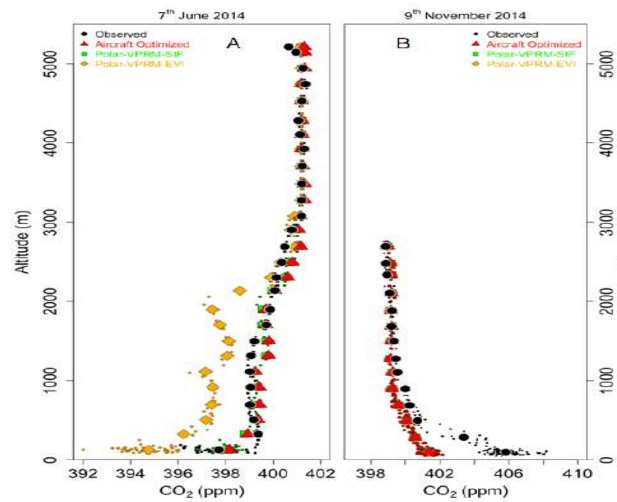

Figure 12. Vertical profiles of CO_2 on the central North Slope on the afternoon of 07 June 2014 (*left*) and 09 Nov 2014 (*right*). The colors show data, WRF-STILT with Polar VPRM driven by EVI and by SIF satellite products, and the profile obtained using the optimized PVPRM-SIF. [from Commane, 2017.]

VI.3 A prior flux fields

A priori flux fields must be combined with calculated surface footprints in order to determine the total contribution to the observed mixing ratios. For CO_2, we will use the Polar Vegetation Photosynthesis Respiration Model (PVPRM) -Solar Induced Fluoresence (SIF), which is optimized to areas of tundra. For CH_4, a large array of models exist, but none have the required granularity and spatiotemporal accuracy to match the PVPRM for CO_2 [Chang, 2014; Miller, 2016], therefore several approaches will be applied.

CO_2 - PVPRM-SIF [Luus, 2017] empirically calculates net CO_2 ecosystem exchange (NEE) at high-resolution (3-hourly and 1/6 x 1/4 degree latitude/longitude grid). PVPRM uses vegetation classes identified from the circumpolar Arctic vegetation map (CAVM; Walker, 2005), which is available 1/120° x 1/120° resolution. PVPRM calculates NEE as the sum of autotrophic and heterotrophic respiration and gross ecosystem exchange (GEE). The diurnal and seasonal variability of NEE are captured using assimilated meteorological inputs (such as air and soil temperature and short-wave (SW) radiation) from North American Regional Reanalysis (NARR; Mesinger, 2006) for the US and Canada.

Respiration is calculated as a linear function of soil temperature during the snow-covered season (winter) and air temperature during the growing seasons. Snow/growing seasons are differentiated using snow cover from MODIS [Hall, 2002]. Photosynthesis (GEE) is calculated as a function of 2 m air temperature, photosynthetically active radiation (PAR, calculated as SW radiation * 1.98), fraction of absorbed PAR (f_APAR), water stress (Pscale, calculated as a function of the MODIS derived land surface water index, (LSWI; Hall, 2002) and light-use efficiency parameters (PAR_0 and λ). These two parameters are different for each ecosystem type and have been determined empirically by fitting to three-hourly observations of CO_2 fluxes and meteorology at tundra and boreal EC sites across Alaska and Northern Canada [Luus, 2017]. f_APAR is calculated using SIF and solar zenith angle (SZA) from GOME-2 [Joiner, 2014] or the OCO-2 (Orbiting Carbon Observatory 2, Frankenberg, 2014) global satellite coverage.

CH_4 - Prior fields for CH_4 emissions should distinguish different source processes: biogenic (wetlands, coastal oceans), thermogenic (natural and human-caused emissions of geologic CH_4), and pyrogenic (created or released by biomass burning). A highly suitable prior such as PVPRM does not exist for CH_4. For wetlands, Chang [2014] examined the predicted emissions from a wide variety of models, including the WETCHIMP suite, and found that none gave a spatial distribution consistent with the CARVE aircraft observations, unlike the excellent fidelity provided by PVPRM for CO_2. Miller [2016] considered this problem in detail and found that a simple flux model based on a daily soil temperature map and a map of wetland extent reproduced atmospheric CH_4 observations in CARVE at the statewide, multiyear scale more effectively than available "process-based" ecosystem models, and suggested that this result points to a simple and effective way of representing CH_4 fluxes across Alaska. The approach in FOCAL is therefore to develop this basic idea at landscape and regional scales as required to improve the fundamentals of CH_4 source modeling and to link to tower- and chamber-based flux measurements made in this proposal, at the Toolik Lake LTER, and at the Barrow Environmental Observatory by the DoE NGEE project (we have good communications with all of these programs). For thermogenic CH_4, the FOCAL measurements of $^{13}CH_4$ and C_2H_6 represent first-impression data that will unambiguously identify thermogenic CH_4 (and CO_2). We will derive the associated fluxes from the ensemble of data, FFM analysis, and remote sensing.

We will develop an empirical prior flux model for inverse modeling of CH_4 fluxes, as the outcome of this study. This prior will utilize the same high-resolution land cover data employed for Polar VPRM, adapted via site-based flux data to capture diurnal, weekly, and seasonal variability.

VII. Broader Impacts

There are several natural extensions to the work and data products from this proposal. Data products from this proposal may be used to evaluate and modify current regional emission models for the Arctic, and ultimately contribute more broadly to the development of robust forecasts of carbon fluxes from this region. Bringing scientists into classrooms and visiting with local groups in the North Slope area is key for the effective union of cutting edge research, local outreach, and public policy. Though not directly funding this work, we will work with NSF's Arctic Research and Education and the North Slope Borough Educational office to identify a few towns in Alaska that we can visit with the Centaur aircraft and present our work through talks and tours of the instrument payload to local populations who are directly affected by the changes to the Arctic. The data products from this proposal can be used to develop forecasts necessary for local populations to understand and predict changes to their environment.

VIII. FOCAL Mission Concept and Deployment Strategy

In order to answer the questions proposed in section II, the proposed campaign involves the use of aircraft measurements from FOCAL coupled with ground-based sensors and multiple modeling strategies. The first year will involve overall system improvement and testing through the use of targeted ground-based sampling coupled with aircraft test flights. While FOCAL has extensive flight hours, our plan is to acquire data and perform complete end-to-end processing to test all of the data interfaces as well as the ability to ingest the data into our modeling framework. The flights will also afford an opportunity to fully test the improvements to the instrument suite as described in section V. In order to minimize risk and simplify the logistics, these flights will take place from Manassas Airport in Virginia where the Centaur aircraft is based. From here we will be able to sample multiple terrain types including Wallops Island where Aurora has permission to fly in restricted airspace at low altitude over the water as well as set up a flux tower in a marsh area.

The full science deployment to the North Slope of Alaska will occur in the summers of 2020 and 2021. We have structured our data collection to maximize flight time and ensure we have the ability for comprehensive measurements to meet our proposed objectives. Our flights will occur from August through the end of September. While we envision approximately 60 days of field deployment each year, our objective is to obtain 30 days of actual measurements with 5 hours of flight per day, accounting for downtime due to weather, pilot rest requirements, and other delays. Flights will focus on areas accessible to Prudhoe Bay, namely the tundra and lakes region of the North Slope and coastal ocean. Areas west of Barrow will be accessed by first transiting to Barrow, refueling, and then proceeding with the science flight mission. Preliminary data analysis for each flight is done in the field and preliminary results are used to help inform future flights. Post mission calibrations, final data analysis, and WRF-STILT model runs are done following each campaign year. Delivery of the data is described in the Data Management Plan.

Eddy covariance towers supplied and operated by NOAA/ATDD will be deployed on the north slope of Alaska in areas accessible from the Dalton Highway. In addition to measuring the fluxes of CO_2 and CH_4, climate drivers such as incoming and outgoing radiation fluxes, water table depth, and other meteorological variables will be recorded continuously. The towers will be sited to measure representative fluxes from both tundra and lakes.

We envision two primary modes of data collection: survey/regional flights and Intensive Observing Periods (IOP)/landscape flights. The overarching objective of survey flights will be to constrain Arctic fluxes over the widest possible geographical area, while the IOPs will be aimed primarily at advancing our understanding of the physical factors (mechanisms) controlling these fluxes in the tundra, lakes, and coast and improving their representation in Earth System Models.

During the regional flights, profiles from the near surface (5-10 m) to above the residual layer (> 1500 m) will be performed to characterize the regional scale fluxes using WRF-STILT. Over the course of the campaign profiles will be obtained throughout the North Slope region with several south of the Brooks Range as well. Several profiles will be obtained at different locations throughout the summer season and also through the diurnal cycle. It is anticipated that at times these regional profiles will be coupled with the IOP flights described below by performing profiles enroute to the target areas and also by flying profiles between the surface and top of the boundary layer between IOP flight legs.

During the IOPs, we will determine local- and landscape-scale surface and ABL fluxes of heat and carbon. These will be at flux altitudes (5-30 m) and will consist of both grid patterns to measure flux over medium scales (50x50 km grid; see Figure 6 for example) and repeated legs over the same location. The focus will be on the space-time variability of fluxes and ABL thermodynamic conditions in order to evaluate downscaling and upscaling approaches, including analyses of temporal and spatial changes in turbulent fluxes as a function of surface morphology, ecosystem properties, and ABL flow conditions. At the 1-km scale, these empirical relationships will be used to evaluate the WRF-STILT model, which in turn will be applied to extend these relationships to larger scales and localities covered by the aircraft measurements.

IX. Summary of Deliverables

- As detailed in the data management plan all primary and secondary data products from the aircraft and towers with be archived for public use. These include concentrations and turbulent winds, and ancillary data such as temperature, pressure, altitude, radiation, etc.
- Running fluxes for each flight conducted at flux altitude and 1-second flux fragments will be calculated and archived along with the associated flux footprints.
- The WRF-STILT model will be run to derive surface influence functions for fluxes derived from inverse models of concentration profiles and these will be archived along with the associated profile data.
- We will develop and publish an empirical prior flux model for inverse modeling of CH_4 fluxes, directly addressing objectives II.2 and II.3.
- Fluxes will be calculated at the local, landscape, and regional scale to be used to answer questions posed in sections I and II.
- Data and analysis comparing the aircraft derived fluxes to local tower measurements and land classification maps and how these vary for different ecotopes will be published in a peer reviewed journal. This will include using the information derived from the isofluxes and ancillary data products to deduce which mechanisms are primarily responsible for the variation in methane emissions. This directly addresses objectives II.1, II.3, and II.4.
- Data, model runs and analysis directly measuring the fluxes over regional scales close to the surface and measuring fluxes using inverse modeling will be compared and published in a peer reviewed journal. This directly addresses objective II.2.
- Data will be used to evaluate which combination of environmental quantities and categorical quantities are best suited for predicting methane emissions to produce more accurate bottom up estimates from remotely sensed variables and will also be compared with existing methane emissions models and will be published in a peer reviewed journal. This directly addresses objectives II.3 and II.4.